EFFECTS OF PILOT INJECTION ON COMBUSTION AND EMISSIONS CHARACTERISTICS USING 2-METHYLFURAN/DIESEL BLENDS IN A DIESEL ENGINE

by

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A direct injection compression ignition engine fueled by diesel blended with 10% or 30% mass proportion of 2-methylfuran was experimentally studied. The in-cylinder combustion pressure, regulated emissions and particulate matter emissions at different pilot injection timings and masses were investigated under the exhaust gas re-circulation mode. It was found the blending with methylfuran increased the peak in-cylinder pressure and retarded the combustion phase at different pilot injection timings. The addition of 30% methylfuran increased the peak in-cylinder pressure and heat release rate gradually along with the advancement of pilot injection timing. The NO_x, HC, and CO emissions increased with the advancement of pilot injection timing when the pilot injection proportion was fixed at 20%, and the blending with methylfuran reduced HC and CO emissions but increased NO_x emissions considerably. The 30% methylfuran addition could significantly reduce nucleation mode and accumulation mode particles at different pilot injection timings and masses compared with pure diesel. In addition, the particulate mass concentration of 30% methylfuranaddition remained at very low levels under all experimental conditions.

Key words: *direct injection compression ignition engine, particulate matter 2-methylfuran, combustion, regulated emissions*

Introduction

The demand for resources has intensified, especially petroleum fuels. In response to the growing utilization of petroleum fuels and the increasingly strict regulations on emissions, researchers have searched for bio-fuels to decrease fuel use and engine emissions [1]. For example, bioethanol featured by renewability and large octane number is commonly used in spark ignition engines [2, 3], and it also used in Diesel engines for study [4]. However, the burning and emission performances of ethanol are severely limited by the low energy density and storage instability [5]. Therefore, researchers are urged to search for superior alternatives to petroleum fuels.

Recently, 2-methylfuran (MF) and 2,5-dimethylfuran (DMF) have been found as promising alternatives for internal combustion engines. In 2009, some improved MF production

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methods were discovered [6-8] and an effective method was further developed to convert fructose into MF or DMF. The abundance and renewability of fructose make MF and DMF renewable fuels. The MF has similar properties as DMF, tab. 1, but MF has more attractive physicochemical properties than bioethanol. For instance, MF has an energy density about 34% higher than bioethanol, which makes it much more cost-efficient. Research on MF is mainly focused on gasoline engines, but rarely on Diesel engines. Thewes *et al.* [9] first reported the higher knock suppression ability and much less HC emissions of MF than gasoline, but the NO_x emission was a concern. Pan *et al.* [10] tested the exhaust gas re-circulation (EGR) rate and compression ratio in a single-cylinder spark ignition engine and found MF outperformed gasoline in increasing the combustion temperature, knocking intensity, cylinder pressure and NO_x emissions at higher compression ratios. Xu *et al.* [11, 12] first found the combustion and emission of DMF were better than gasoline in a direct injection spark ignition engine. They also found dual-injection outperformed direct injection in terms of higher thermal efficiency and slower gasoline-DMF consumption [13]. The authors recently investigated the emission and combustion of diesel-MF blends and diesel-DMF blends in a direct injection compression ignition (DICI) engine, and found that MF addition retarded the combustion phase of blended fuels and increased the brake thermal efficiency of diesel engine [14]. Diesel-MF or diesel-DMF [15] blending promoted NO_x emissions but decreased soot emissions significantly. As for the unregulated emissions, diesel-DMF blending increased the acetaldehyde emissions, while the benzene and 1.3-butadiene emissions were reduced compared with pure diesel [16].

The multiple-injection strategy is widely investigated to decrease soot and NO_x emissions and combustion noise [17]. This study was aimed to assess the effects of pilot injection on cylinder pressures and exhaust emissions in a diesel engine fueled with diesel-MF blends with the technique of EGR, and few studies have been reported in this field.

Table 1. Properties of MF, DMF, diesel and bioethanol [4, 5 , 16 , 18 , 19]

Parameter	MF	DMF	Diesel	Bioethanol
Chemical formula	C_5H_6O	C_6H_8O	C_{12}-C_{25}	C_2H_6O
Research octane number	103	101	20-30	109
Oxygen content [%]	19.51	16.67	0	34.78
Motor octane number	86	88	–	90
Cetane number	–	9	52.1	8
Octane number	–	119	–	108
Stoichiometric air/fuel ratio	10.05	10.79	14.3	8.95
Density at 20 °C [$kgcm^{-3}$]	913.2	889.7	826	790.9
Energy density [MJL^{-1}]	34.8	31.5	34.92	23
Water solubility [wt.%, 20 °C]	Negligible	Negligible	Negligible	Miscible
Latent heating [$kJkg^{-1}$] at 25 °C	358	332	270-301	919.6
Lower heating value [$MJkg^{-1}$]	31.2	33.7	42.5	26.9
Auto-ignition temperature [°C]	–	286	180-220	434

Experimental

Engine and instrumentation

Table 2 lists the main specifications of the DICI engine containing a high pressure rail injection system, fig. 1. In-cylinder pressures were recorded by a Kistler 6025C piezoelectric pressure transducer, amplified with a Kistler charge amplifier and received by a CB-466 combustion device. The intake air temperature and pressure were regulated by an air conditioning system and a supernumerary compressor. Engine working parameters (*e. g*. EGR rate; and timing and mass of pilot injection) were controlled by the electrical control unit (ECU).

Table 2. Engine specification

Type of engine	4-cylinder, four-stroke
Stroke [mm]	103
Bore [mm]	96
Displacement [cc]	2982
Compression ratio	17.5
Rated power [kW]	85
Type of ignition	Compression ignition
Rated speed [rpm]	3200
Maximum torque [Nm]	300
Main injection	7.5 Crank angle degrees bTDC
Method of starting	Electric start

Exhaust emissions were measured by an AVL gas analyzer, with resolution of 1 ppm (NO_x), 1 ppm (HC), and 0.01% (CO). Particulate matter (PM) emissions were measured by a DMS500 differential mobility spectrometer with uncertainty of 5% for particles smaller than 300 Nm and 10% for larger ones. The DMS500 has a two-stage dilution system, the first dilution factor was set to five throughout the experiment and the second dilution factor was selected to guarantee the particle concentration is within the test range of it.

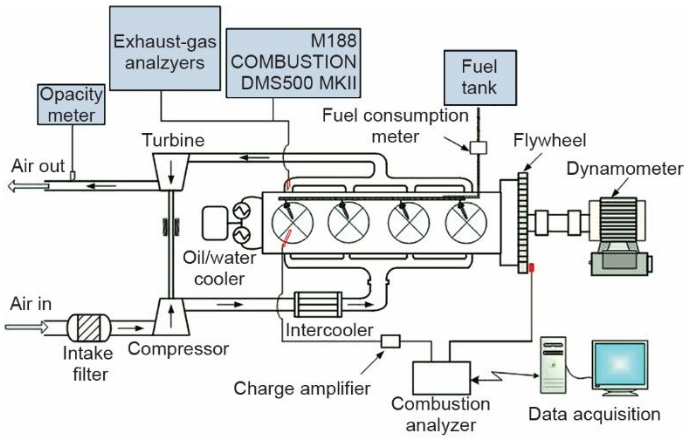


Figure 1. Schematic of engine and instrumentation set-up

Fuels and testing process

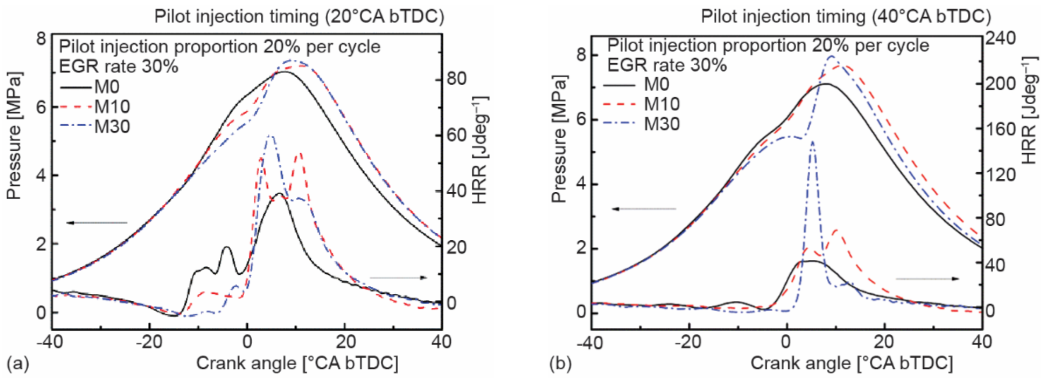
The MF (99.9% purity, TZHL Biological Technology Co. Ltd.) and diesel (China Petroleum and Chemical Corporation) were used in this study. Different mass fraction of MF (0%, 10%, and 30%) with diesel were blended, referred as to M0, M10, and M30, respectively.

The operating conditions were set at engine torque of 90 Nm (brake mean effective pressure = 0.38 MPa) and engine speed of 1800 rpm, the EGR rate was set at 30% (maximum EGR rate of the engine). The start of pilot injection timing sweep varied from 20 to 60 crank angle (°CA) bTDC at an increment of 10 °CA and the pilot injection proportion was 10% or 20% of fuel supply amount per cycle, while the start of main injection timing was 7.5 °CA bTDC. The lubricant oil, coolant, and engine intake air were maintained at 89±1, 86±1 and 25±0.5 ºC, respectively. In order to ensure the reliability of results, each measurement was repeated 20 times.

Results and discussion

In-cylinder pressure

The in-cylinder pressures and HRR of three test fuels at 20, 40, and 60 °CA bTDC pilot injection timing are presented in fig. 2(a)-2(c). At 20 °CA bTDC, fig. 2(a), the peak in-cylinder pressure rose obviously and the burning of main injection was postponed with the rise of MF mass fraction. This is mainly attributed to the low ignition performance and high oxygen content of diesel-MF blends. The lower cetane number and higher vaporization latent heat of MF further delayed the ignition [19]. Blending with MF prolonged the main injection ignition delay and more pre mixtures were produced. The high oxygen concentration accelerated combustion process for diesel-MF blends, the heat release was quickened and the in-cylinder pressure was increased.



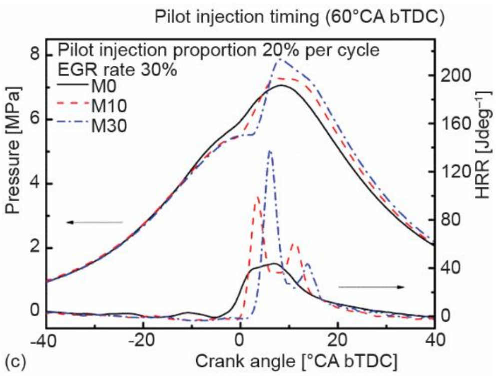


Figure 2. Cylinder pressures and HRR of three fuels at (a) 20, (b) 40, and (c) 60 °CA bTDC pilot injection timing

Similar to 20 °CA bTDC pilot injection timing, diesel-MF blends increased the peak in-cylinder pressure and retarded the starting of ignition when the pilot injection timing is 40, fig. 2(b) and 60 °CA bTDC, fig. 2(c), and without significant differences in combustion phase among the three fuels. Besides, the peak HRR increased gradually for M10 and M30, but did not noticeably change for M0 as the pilot injection timing was advanced.

Figure 3 shows the in-cylinder pressures and HRR of M30 at different pilot injection timings. For M30 with 10% pilot injection proportion, fig. 3(a), the peak in-cylinder pressure was enlarged gradually and the burning began at a later CA as the pilot injection timing was advanced especially between 20 and 30 °CA bTDC. This was because the pilot injected fuel combustion imposed a smaller preheating effect on the main injection fuel and the lower in-cylinder temperature inhibited the ignition of M30 as the interval between pilot and main injection was prolonged. Besides, the maximum HRR decreased significantly with the retarding of pilot injection timing, which can be explained by the effect of high compression temperature on ignition performance overwhelmed that of low cetane number or high vaporization latent heat of MF when the pilot injection timing was close to the TDC. In addition, the burning of pilot injected fuel was unobvious or even stopped, and its preheating effect on main injection was weakened as the pilot injection timing distanced from the top dead center. More pilot injected fuels were involved into the combustion process of the main injected fuels, which increased the maximum HRR.

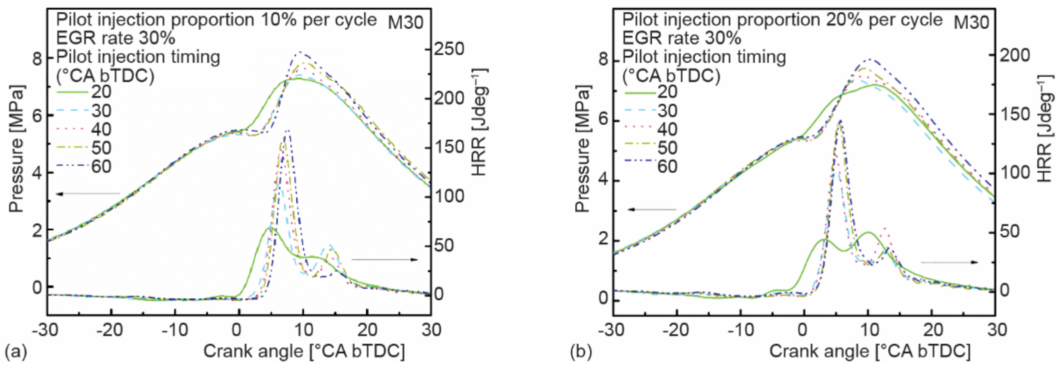


Figure 3. Cylinder pressure and HRR of M30 at different pilot injection timings with pilot injection proportion of (a) 10% and (b) 20%

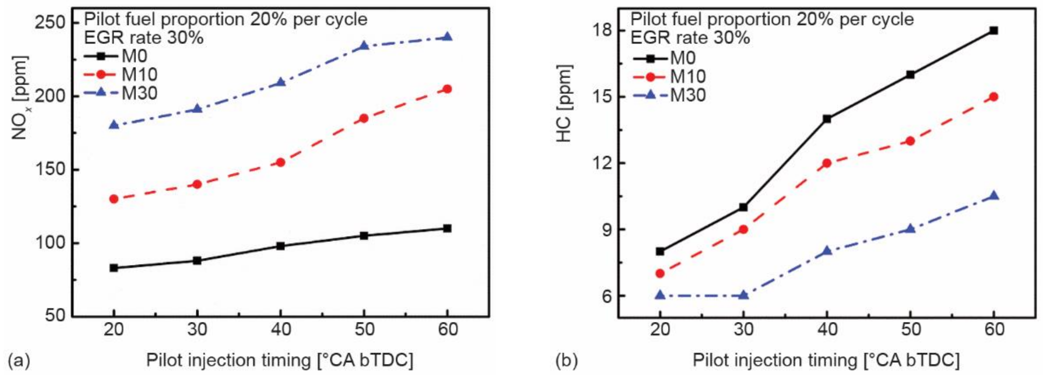
Like the 10% pilot injection proportion, the maximum in-cylinder pressure and HRR for M30 with 20% pilot injection proportion, fig. 3(b), were also increased with the proceeding of pilot injection timing. However, the starting timings for combustion were not obviously different between 30 to 60 °CA bTDC pilot injection timing. The reason may be that the preheating effect of pilot injection fuel was enhanced under the condition of large amount of pilot injection fuel.

Regulated emissions

The NO_x, HC, and CO emissions from tested fuels were also investigated at different pilot injection timings when the pilot injection proportion is 20% per cycle and EGR rate is 30%.

Figure 4(a) shows the variation of NO_x emissions at different pilot injection timings for three fuels. The NO_x emissions are significantly affected by oxygen concentration of fuel, burning temperature, and residence time in the high temperature region [20]. This study showed

NO_x emissions from all three test fuels were increased with advancement of pilot injection timing. The MF blending promoted NO_x emissions compared with M0, reasons can be explained by following. First and foremost, the high combustion temperature caused by the promoted premixed combustion for diesel-MF blends increased NO_x emissions. Secondly, the high oxygen content in MF provided the oxygen condition for NO_x emissions. Thirdly, the higher H-C ratios generally correspond to lower NO_x emissions [21], while the low H-C ratios in diesel-MF blends increased NO_x emissions. In addition, EGR and pilot injection strategies significantly reduced NO_x emissions, especially for M0 compared to authors' previous studies [14].



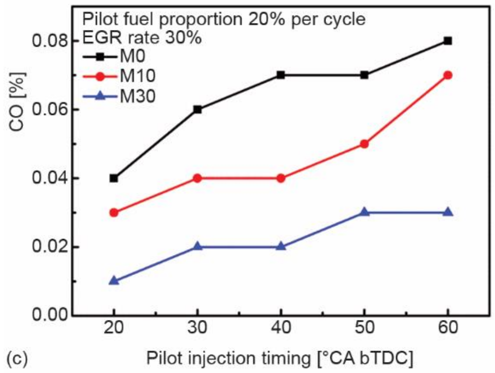


Figure 4. Variation of (a) NO_x (b) HC, and (c) CO emissions from different fuels along with pilot injection timing

Figure 4(b) shows the effects of different pilot injection timings and MF addition on HC emissions. Clearly, HC emissions were gradually promoted as the pilot injection timing was advanced, which was mainly attributed to the flame quenching and delayed ignition. The spray penetration would be enlarged with the advancement of pilot injection timing because of the lower in-cylinder pressure. When the flame approached the combustion chamber wall, the temperature of mixtures were too low to be fully burnt and left a layer of unburned substances, which promoted HC emissions. Meanwhile, more mixtures were pressed into the crevices of the combustion chamber with further delay of ignition during the compression stroke, which missed the primary burning and also promoted HC emissions. The lower HC emissions for blended fuels can be attributed to the following reasons. Firstly, higher combustion temperature caused by diesel-MF blends strengthened the post oxidization of HC emissions. Secondly, higher oxygen concentrations in diesel-MF blends could also promote the oxidization of HC emissions. Thirdly, MF addition increased the volatility of blended fuels and helped to reduce HC emissions [22].

Figure 4(c) shows the effect of pilot injection timing and MF addition on the emission of CO, which is a product of incomplete combustion [23]. Clearly, CO emission increased gradually with the advancement of pilot injection timing for all three test fuels but without obvious increments, and reduced significantly by MF addition. Like HC emissions, the incomplete combustion caused by high level of cylinder and piston wall wetting as the pilot injection timing advanced away from the TDC, which promoted CO emissions. At the same pilot injection timing, the higher volatility of diesel-MF blends raised the homogenous level and reduced the wetting of cylinder and piston wall, which promoted complete combustion and reduced CO emissions.

The PM emissions

Generally, particle size distribution can be divided into the nucleation mode (D_p = 5-50 nm) and accumulation mode (D_p = 50-1000 nm) [24]. The effects of MF addition on PM emissions at different pilot injection timings and masses were also investigated. Since the particle size distribution mainly fell within 0-500 nm, the range of PM from 500 to 1000 nm was not shown here. Figure 5 shows the particle size distributions and particle number concentrations of the three test fuels at 20, 30, and 50 °CA bTDC pilot injection timings, at a pilot injection proportion of 10%, figs. 5(a), 5(c), and 5(e), and 20%, figs. 5(b), 5(d), 5(f) per cycle.

The M10 has a peak nucleation mode concentration similar to that of M0 when the pilot injection timing was 20 and 30 °CA bTDC, and its accumulation mode concentration was the lowest among all test fuels at different pilot injection timings. The reason is that fewer local-richness regions of M10 inhibited the surface growth and coagulation of primary particles, and the higher oxygen content in M10 compared with M0 also reduced the formation of accumulation mode particles. The M10 has a peak nucleation mode concentration much higher than M0 at the pilot injection timing of 50 °CA bTDC. Reasons are that first, the ignition delay of main injection caused by the low cetane number and high vaporization latent heat of M10 was prolonged as the pilot injection timing advanced away from the TDC, which reduced the formation of accumulation mode particles and the nucleation mode particles were relatively increased. Secondly, the higher oxygen content and higher combustion temperature of M10 inhibited the growth of primary particles and promoted the production of nucleation mode particles accordingly.

The nucleation mode and accumulation mode concentrations of M30 are significantly lower than M0 except at the pilot injection timing of 50 °CA bTDC with pilot injection proportion of 10%. Three reasons can explain this phenomenon. Firstly, the long main injection ignition delay and high volatility of MF promoted the evaporation and atomization of diesel-MF blends, which decreased local-richness regions and inhibited the formation of particles. Secondly, the soot precursors such as acetylene and propargyl would reduce by the effect of intramolecular oxygen in MF. The highest oxygen content in M30 raised the combustion temperature and promoted the oxidation process of particles. Thirdly, MF is aromatic-free fuel, the addition of MF to pure diesel diluted the aromatic content in blended fuels, while the high aromatic content is beneficial to the formation of PM emissions.

The M30 could reduce nucleation mode particles significantly but increase the accumulation mode particles compared with M10 at different pilot injection timings. Results indicated that larger MF addition could significantly reduce the number concentrations of soot particles. Moreover, the PM emission variation trends did not change significantly among the three test fuels for pilot injection proportion of 10% and 20% at the same pilot injection timing.

The M30 was also compared with M0 to study the effects of large MF addition on PM emissions. The variations of nucleation mode, fig. 6(a) and accumulation mode, fig. 6(b), concentrations of M0 and M30 at different pilot injection timings are displayed in fig. 6. Clearly,

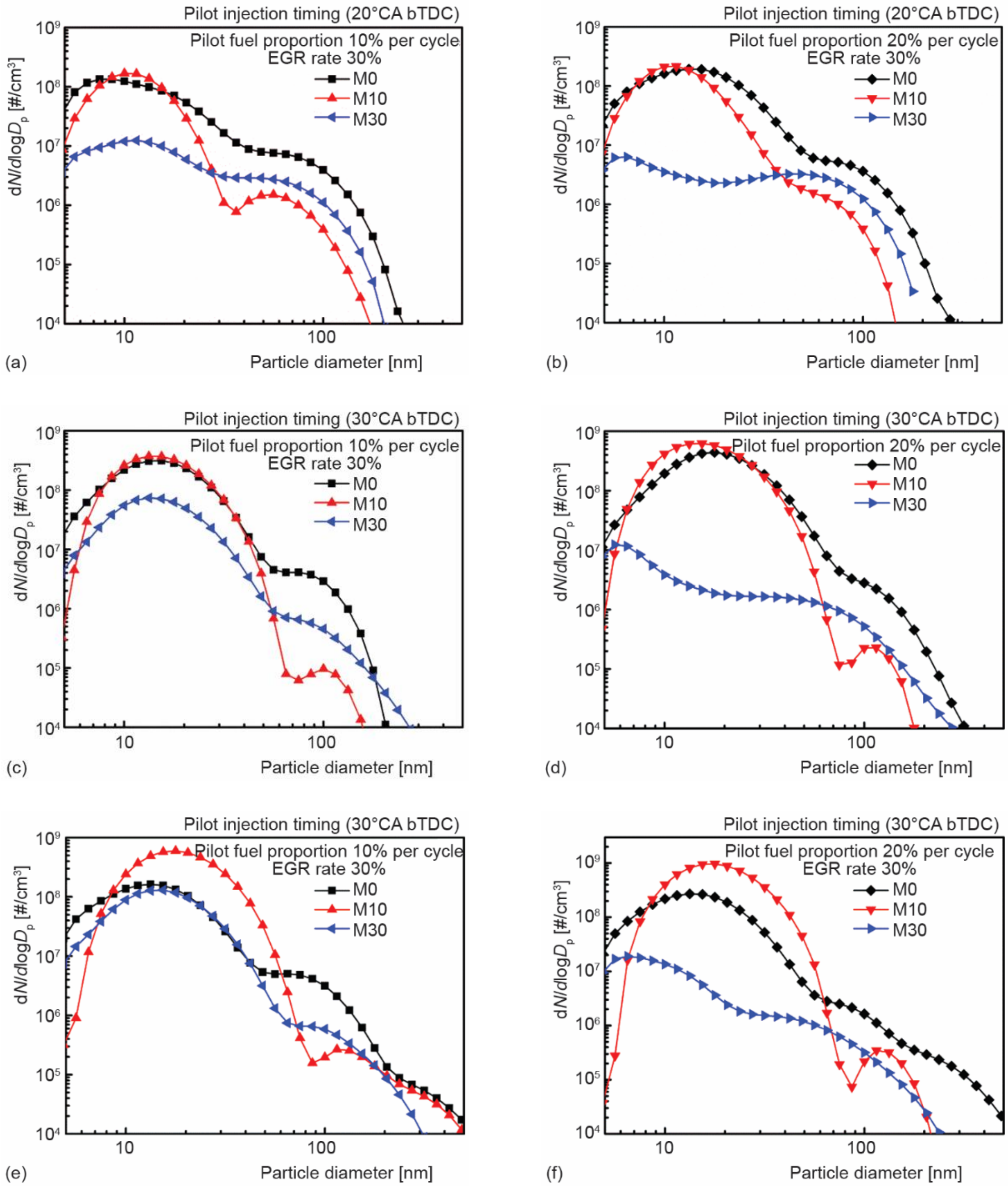


Figure 5. Particle size distributions of test fuels at 20, 30, and 50 °CA bTDC pilot injection timing

the nucleation mode concentrations of M0 and M30 both increased first and then declined with advancement of pilot injection timing except for M30 with 20% pilot fuel proportion at 60 °CA bTDC. While the accumulation mode concentrations declined first and then increased slightly except for M0 with 20% pilot fuel proportion at 60 °CA bTDC. This is because the flame generated by the pilot injected fuel enwrapped the main injected fuel when the interval between the pilot and main injections were short. As previously described, more fuels would approached to

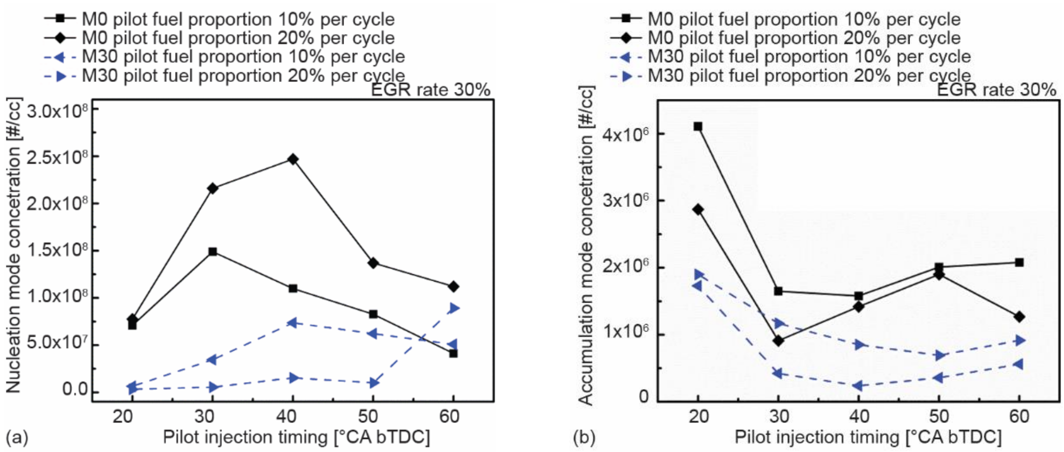


Figure 6. (a) Nucleation mode and (b) accumulation mode concentrations of M0 and M30

the combustion chamber wall with the advancement of pilot injection timing because the long spray penetration caused by lower in-cylinder pressure, which also promoted PM emissions especially accumulation mode particles.

The M30 reduced PM emissions compared with M0, which was mainly attributed to the better physicochemical properties of blended fuels. As shown previously, the high volatility, long main injection ignition delay, high oxygen content and low aromatic content of M30 reduced PM emissions significantly compared with M0. Soot emissions in diesel engines result from the balance between soot formation and oxidation [25]. Oxygen blends is key factor in reducing PM emissions. The reduction of soot particles depend on the higher oxygen mass fraction in blended fuels, but less on the type of oxygen [26]. For M30, the oxidation-control of particles surpassed formation-control, which reduced PM emissions significantly.

Effects of MF addition on PMC at different pilot injection timings and masses are showed in fig. 7. As showed in fig. 7(a), when the pilot injection proportion was 10%, PMC of M0 and M10 increased first and then decreased with the advancement of pilot injection timing, while the variations of PMC of M30 were small. Similarly, when the pilot injection proportion was 20%, fig. 7(b), M10 still had a similar trend with pure diesel except for 60 °CA bTDC, and the PMC of M30 was the lowest within three test fuels.

Results indicated smaller MF addition still had the similar PMC variation trend to that of pure diesel, and the PMC of M10 decreased to a certain extent. This is because smaller MF addition changed the physicochemical properties of blended fuels slightly, and the better physicochemical properties of MF played a key role in reducing PMC for M10. The PMC of M30 was decreased significantly compared with M0, which was mainly because the physicochemical properties of blended fuels changed greatly when the proportion of MF in the blended fuels was 30%.

Conclusions

- The MF addition increased the peak in-cylinder pressure at different pilot injection timings. The lower cetane number and higher vaporization latent heat of diesel-MF blends delayed the start of combustion.
- The HRR and peak in-cylinder pressure of M30 increased gradually with the advancement of pilot injection timing, and the premixed combustion was increasingly obvious.

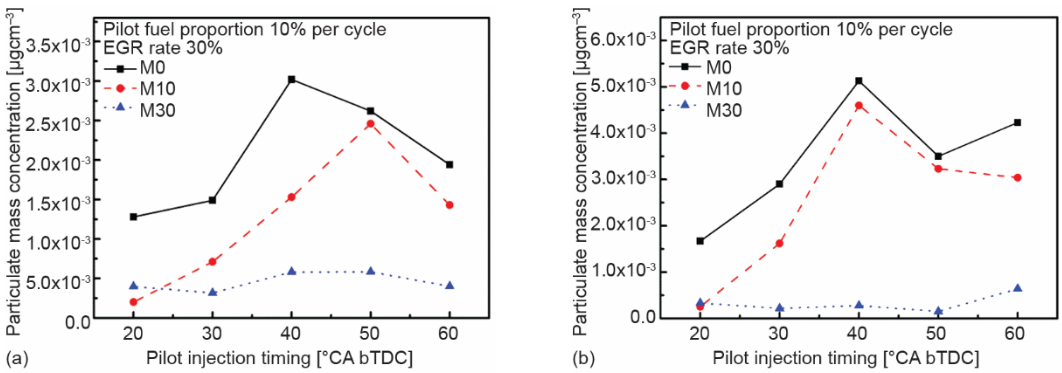


Figure 7. Effects of pilot injection timing on particulate mass concentration of three fuels at pilot injection proportion of (a) 10% and (b) 20%

- The NO_x, HC, and CO emissions were promoted by the advancement of pilot injection timing when the pilot injection proportion was 20% per cycle; MF addition inhibited HC and CO emissions but accelerated NO_x emissions; NO_x emissions were reduced significantly with the technique of EGR.
- The M10 reduced the accumulation mode concentration of PM emissions significantly while M30 reduced the nucleation mode concentration compared to pure diesel; the PM emission variation trends of three tested fuels did not change significantly between pilot injection proportions of 10% and 20% at the same pilot injection timing.
- Compared with pure diesel, M30 could reduce nucleation mode and accumulation mode particles obviously; the PMC of M30 was significantly lower than M0 and M10 due to better physicochemical properties for MF.

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